17.5 Design of Sustainable Industrial Systems by Integrated Modelling of Factory Building and Manufacturing Processes

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Abstract

This paper presents an integrated approach that combines 'Sustainable Building Design' tools and 'Sustainable Manufacturing Process' tools to create a tool for the design of sustainable manufacturing systems.' Currently no such integrated tools are in use by manufacturers to assess energy performance, identify improvement areas and help suggest actions. This paper describes the development of a tool that through such integrated modelling can help identify improvements via its library of tactics. These sustainable manufacturing tactics have to account for location and time, as well as production process, in a manner that is not currently supported by either manufacturing process simulation tools, or building energy tools. Through case study applications, the integrated modelling of real world industrial processes is demonstrated, from target and boundary settings, mapping (manufacturing process systems, material flow, surrounding buildings and facilities), data collection, simulation, improvement opportunities and optimisation.

Keywords:

Sustainable manufacturing, factory modelling, energy modelling, sustainable manufacturing tactics, resource flows

1 INTRODUCTION

Industry consumes around one third of the world's energy and accounts for almost 40% of global carbon dioxide emissions (CO_2) [1]. Depending on manufacturing activity, the primary energy consumption of a country's industrial sector varies in relation to the global average, e.g. China (≈48%), Germany (≈23%), USA (≈20%) [1]. In the UK, industry consumes approximately 20% of the UK's primary energy, with industries such as; production of coke, refined petroleum products, nuclear fuel, chemicals, man-made fibres, food and beverages, base metals and other minerals, pulp and paper products, rubber and plastic accounting for around 70% of industrial energy use [2]. Further aggregation of the UK industrial energy figures indicates that in 2008, nearly 50% of primary industrial energy was consumed by heating processes (high and low temperature) and that building related energy (space heating and lighting) accounted for 12% [2]. In some of the UK's manufacturing industries building related energy exceeded process energy. The growing concern over climate change, resource depletion and rising energy prices has lead to renewed focus on global industry. It is reported that industry can make potential savings of 25% by 2020. Improvement potentials identified are; process optimization (25-30%), optimised logistics (16%), integrated process chains (30%), development of new products (10-40%), intelligent motor drives (20-40%) and alignment with best performers (15%) [3].

Figure 1 gives an overview of building and process related energy domains that exist in manufacturing. Four areas are identified: building, building services, manufacturing processes and manufacturing plant. The buildings technical services are designed to meet the requirements of the internal environment of the building. The technical services may also share common elements with the manufacturing plant (e.g. hot/cold water circuits, steam etc) facilitating manufacturing processes.

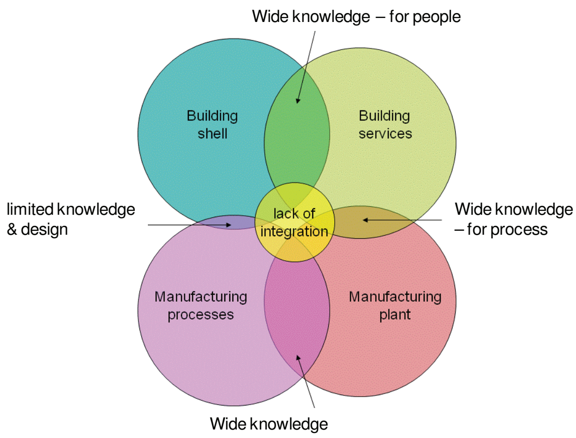

Figure 1 - Knowledge overlaps between energy domains in manufacturing [4]

Figure 1 highlights the overlap in knowledge between the four domains related to the use of energy in the buildings and processes of manufacturing. There is limited knowledge and design between the building shell and manufacturing processes and also the coupling of the four domains (the central yellow circle).

This paper presents an integrated approach that combines 'Sustainable Building Design' tools and 'Sustainable Manufacturing Process' tools to create a tool for the design of sustainable manufacturing systems.' Currently no such integrated tools are in use by manufacturers to assess energy performance, identify improvement areas and help suggest actions. Additionally, there are few examples of research [5-8] to bring these domains together. Section 2 describes a brief overview of the features and workflow of an integrated sustainable manufacturing tool. Section 3 discusses two applied industrial based studies using the methods described in Section 2. Conclusions are drawn in Section 4 and future works in Section 5.

2 INTEGRATED APPROACH

The work presented in this paper is part of a wider project called THERM (THrough-life Energy and Resource Modelling) [9]. THERM is a collaborative project between UK industry and academia and is partly funded by the Technology Strategy Board. The project will deliver a software tool that is in advanced stages of coding and which will reside within an existing building energy modelling suite [10]. This paper describes the development of the THERM tool that through such integrated modelling can help identify improvements via a library of 'tactics'. The following section explains the main features of the integrated tool.

2.1 Building modelling tool

The existing building modelling suite is based on a bulk air flow approach. Rooms are represented within the tool as thermal zones. A bulk air flow model calculates the properties of air at a single air mass node per zone (e.g. temperature and humidity). The air is considered to be fully mixed and is directly influenced by convective heat transfer. Surface temperatures are influenced via long wave radiation exchanges between internal and external surfaces and from other sourced gains. Heat transfer through conduction at boundary and internal walls is also modelled via the inclusion of thermal mass based on a combination of finite difference explicit and implicit time-stepping methods. For further information on the energy balance of a typical built environment, see [11]. A sustainable manufacturing modelling tool must be capable of modelling the interaction between the production system and its physical environment. Through use of a building modelling tool, convection and long wave radiation heat transfer from manufacturing processes, plant and material flow can be coupled with their surrounding and physical environment, Figure 2. This approach enables energy balance exploration studies between the building technical services and production systems. The mapping of processes, plant and material within a building modelling tool also defines the locality of production systems. Further opportunities may be sourced through synergies between uncoupled production systems and building technical services.

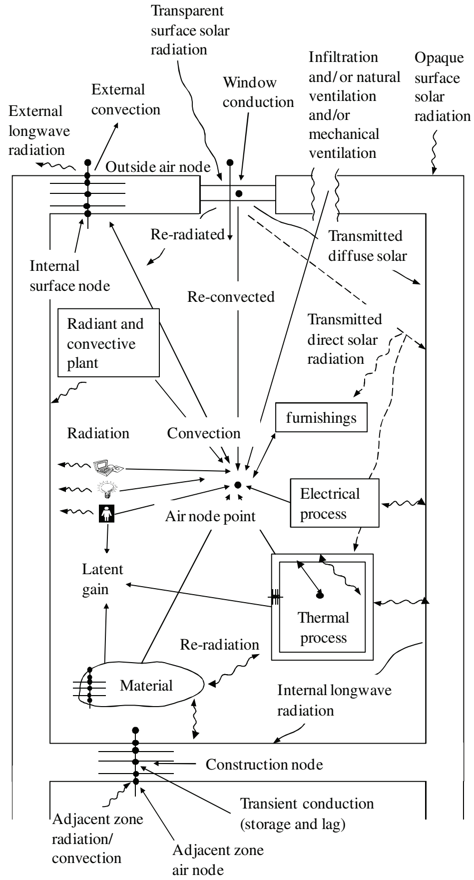

Figure 2 - Schematic of the overall energy flow paths of a factory environment [12]

2.2 Process and material

At time of writing, a new tool within the existing building energy modelling suite is being coded. The tool consists of three approaches to modelling manufacturing processes, plant and material flow within the existing building modelling suite. The first approach is based on production system inputs and outputs driven from a database containing product, material and energy data. A manufacturing process (illustrated by the blue central box in Figure 3) receives profile driven inputs of energy, material and heat; and outputs of material and heat. Heat identified as leaving the production system, couples with thermal energy flows from its surrounding environment. Depending on what is known about a production system such as metered consumption data, production schedules, manufacturing plant components etc; the inputs and outputs can represent a production system at a macro or micro level. A second approach models the production system as a thermal zone within the existing capabilities of the building modelling suite. At present, the building modelling tool only considers air based models with an air node upper temperature limit of 100ºC. This method can combine with approach one, placing the production system within the thermal zone. The air temperature of the thermal zone is controlled via time variant profiles. Production system parameters such as energy, material and heat flows are represented via the database inputs and outputs.

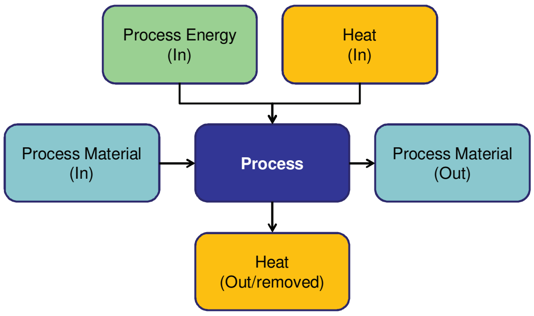

Figure 3 – Production system database

The third approach goes beyond the temperature control strategy of the thermal zone, discussed in approach two, through modelling of complete heating, ventilation and air conditioning (HVAC) networks. This approach still incorporates approach one; however energy and heat inputs from production system plant are modelled by the HVAC network application. The crossover between building technical services and manufacturing plant can be explored through modelling of system distribution networks.

2.3 Library of tactics

The aim of the tactics library is to provide the mechanisms for resource efficiency improvement [13]. Tactics have been created from a large database of sustainable manufacturing practices collected from academic and trade literature. The nature of each literature source and the level of detail varied significantly from one case to another. Some reports contained detailed information such as initial investment cost, operational and maintenance costs, and annual savings in terms of water, material, energy and cost. In most cases the reports described the end result of the improvement activities and not a method for identifying the improvement in the first place. Moreover, all collected cases reported were success stories with no mention of challenges, difficulties or barriers to implementation, and no reported case of failure.

Initial analysis filtered cases reporting practices outside the scope of this study (e.g. off-site activities). The tactics have been identified by classifying the practices based on their commonalities, the drivers of change and the mechanisms for implementing the practices. As the tactics cover generic and various technological solutions and resource flows, the number of tactics formulated was as low as 20 (Table 1). Therefore, a large number of practices can be identified by looking at few variables and using simple rules. The tactics library is structured according to an improvement hierarchy (adapted from energy/waste hierarchies): prevent, reduce, reuse, and substitute. It shows the preferred priority order for implementing tactics and thus supports decision-making for sustainable improvements.

The first type of improvement recommended is *Prevention*. Prevention tactics aim at avoiding resource use at the source by eliminating unnecessary process or stopping equipment when not in use.

The second and third types of improvement are *Reduction*. Waste reduction tactics aim at waste generation reduction through good housekeeping, repair and maintenance practices. Usage reduction tactics aim at improving efficiency through optimised production schedule and start-up procedures. They also identify mismatches at supply and demand levels.

The fourth type of improvement is *Reuse*. The tactics of this type identify compatible waste output and demand, where and when waste is generated and whether waste can be reused as a resource input elsewhere considering the complexity of the system.

Finally the fifth type of improvement is *Substitution*. Substitution tactics aim at improving the environmental performance of the system by changing supply or process, e.g. renewable and non-toxic inputs, high efficiency processes and best available technology.

Table 1 - Library of sustainable manufacturing tactics [13]

Prevention (avoid usage)
• Remove unnecessary resource usage • Remove unnecessary technology • Align resource input profile with production schedule • Switch off/standby mode when not in use
Reduction (waste output)
• Waste collection, sorting, recovery and treatment • Repair and maintain
Reduction (resource flow)
• Optimise production schedule to improve efficiency • Optimise resource input profile to improve efficiency • Change set points/running load • Monitor performance • Control performance • Change resource flow layout • Change technology layout
Reuse (waste as a resource)
• Synchronise waste generation and resource demand to allow reuse • Reuse waste output as resource input
Substitution (new resource or technology)
• Replace resource input for better one • Replace technology for better one • Add high efficiency resource • Add high efficiency technology • Change the way the function is accomplished

2.4 Workflow

The workflow shown in Figure 4 guides the user through the stages of modelling a production system and incorporates the tactics to support the identification of improvement opportunities.

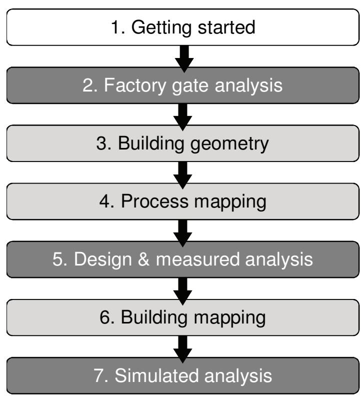

Figure 4 – Workflow guiding through factory modelling (light grey) and analysis (dark grey) for resource efficiency

The first stage is *Getting started* which consists of defining the scope of the analysis and setting targets. For instance, targets can be CO_2 emission reduction, energy cost reduction, water preservation or waste avoidance. System boundaries are typically delimited by a physical area of the factory, a production line or specific processes.

The second stage is *Factory gate analysis*. No model geometry is required at this stage. Site metered data is needed for early analysis, e.g. "low hanging fruit" improvement opportunities and easy wins.

The third and fourth stages of the workflow consist of creating the *Building geometry* and the *Process map*. At these stages, building geometry and process data are integrated into the model to enable further detailed analysis. Resolution is a key issue as the efforts placed in creating the model must be balanced with the level of response expected from the analysis. During process mapping, the HVAC model can be coarse since no simulation is required. However heating and cooling sources must be defined so they can be referred to in the process mapping.

The following stage is *Design & measured analysis* during which higher resolution review of meters and sub-meters against process design data is conducted to identify more improvement opportunities.

The sixth stage is *Building mapping*. In order to populate the thermal model and to prepare for simulation, detailed building and HVAC data are needed: room conditions and activities (e.g. temperature, occupancy, lighting), construction (e.g. material properties: thermal mass, U value), HVAC systems (e.g. boiler, chiller, fan, HVAC network layout and schematics), control arrangements, etc.

The final stage is *Simulated analysis*. It includes both thermal and process simulations to identify advanced improvement opportunities. The extent of the analysis can vary from whole site to specific process. This stage can be repeated to explore what-if scenarios after improvement implementation.

3 CASE STUDIES

The integrated modelling of industrial processes has been developed and is demonstrated using case studies. Case studies obtained from the industrial partners of the THERM project are discussed below. Case studies have been developed by identification of tactics through extensive discussions with industry experts and a combination of studies using development prototypes of the THERM tool, Excel and Matlab/Simulink.

3.1 Industrial drying tank

Figure 5 illustrates an industrial drying tank. The purpose of the drying tank is to dry product that enters the process in a wet state. This is achieved by circulating warm air supplied to the drying tank from the re-circulated network of induction fan, heat exchanger (HX) and re-circulation ductwork. The figure illustrates the coupling of thermal energy flows between the drying tank process and surrounding environment. The illustrative line widths do not represent quantity of flow [14].

Design and measured analysis (Figure 4) has been carried out using existing data in the form of: production schedule data, capacity ratings of the induction fan and HX, air flow rate of the system including re-circulated air and drying tank air temperature set-point. From the collection of data, the drying tank process has been modelled using the existing software capabilities of the building modelling suite and part coded THERM tool for representing production systems via a database, Figure 3. The drying tank is represented as a thermal zone surrounded by the larger thermal zone of the factory. The plant of the drying tank has been modelled as an HVAC network consisting of: induction fan, HX and recirculation ductwork. Material flow into and out of the drying tank is represented via a database, formed from one week of production schedule data.

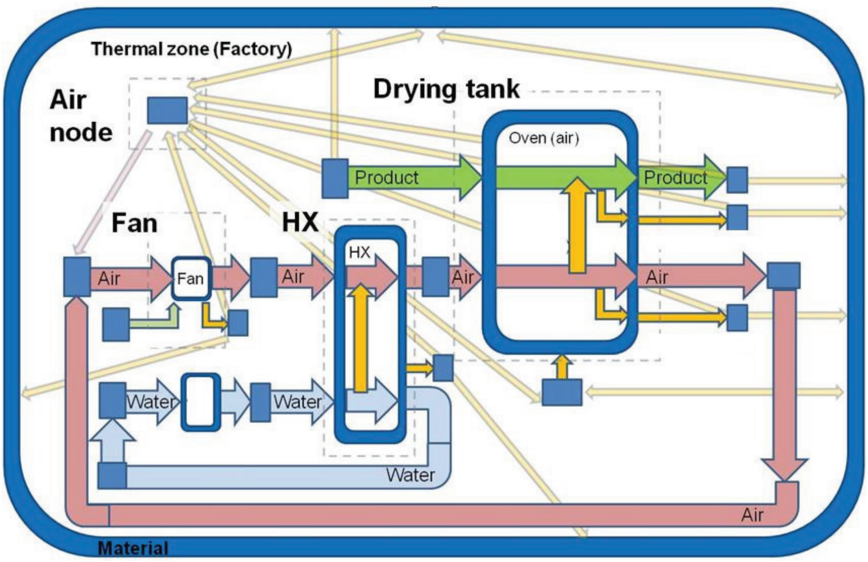

Figure 5 - Graphical representation of a drying tank and plant, defined by its location (thermal zone) [14]

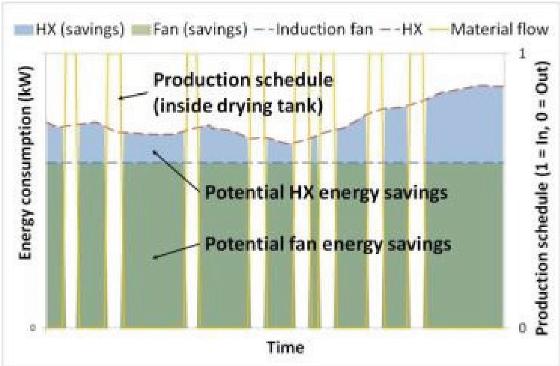

Figure 6 – Prevention tactic

A first pass of the library of tactics (Table 1) identified an opportunity to reduce the energy consumption of the induction fan and HX via the tactic prevention - align resource input profile with production schedule. Figure 6 illustrates the mismatch of production schedule and resource input. There are potential energy and resource savings when there is no product being dried within the process, illustrated in the figure by the filled areas: fan (green) and HX (blue). Simulated results predict a 74% energy savings from one week of data. Future work is to collect additional metered data from the drying tank plant to enable access to further tactics as well as validating the findings of the case study.

3.2 Air supply house (ASH)

Figure 8 illustrates an industrial ASH process consisting of the following manufacturing plant: gas burner, humidifier, steam injection, closed loop chiller and closed loop steam reheat. The ASH process conditions external air to achieve temperature and humidity conditions within a psychrometric control window (Figure 7) by passing the air through a sequence of plant before supplying it to the desired destination (see Figure 8). Figure 7 illustrates the psychrometric behaviour and sequence of plant: gas burner (1), humidifier (2), steam injection (3), closed loop chiller (5) and closed loop steam reheat (4). The blue circles represent warm/moist (upper right) and cold/dry (lower left) inlet conditions of the external air. Depending on the condition of external air not all of the sequenced plant is required.

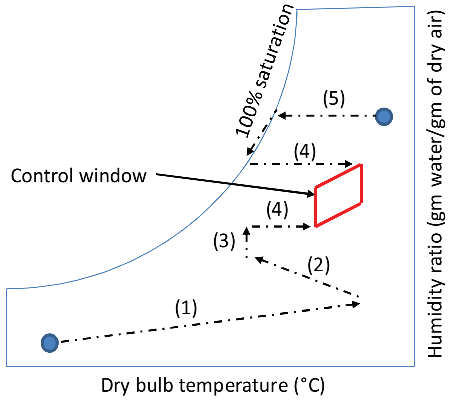

Figure 7 – Psychrometric chart with control window

Design and measured analysis (Figure 4) has been carried out using the building modelling HVAC network and Matlab/Simulink. Preliminary analysis has identified two tactics: reduction and substitution (Table 1). Reduction implies optimisation of the resource input profile to improve efficiency, which would be achieved through conditioning of the external air to the minimum control window settings. Substitution implies replacing resource input or replacing technology, which would be achieved by replacing the boiler that supplies steam. The demand side energy consumption of the ASH unit is shown in Figure 9 (upper red line). Potential energy savings of 25% have been identified through simulation based on the final air condition being treated to the minimum control window setting (bottom blue line). Further investigational work is required on-site to validate case study findings.

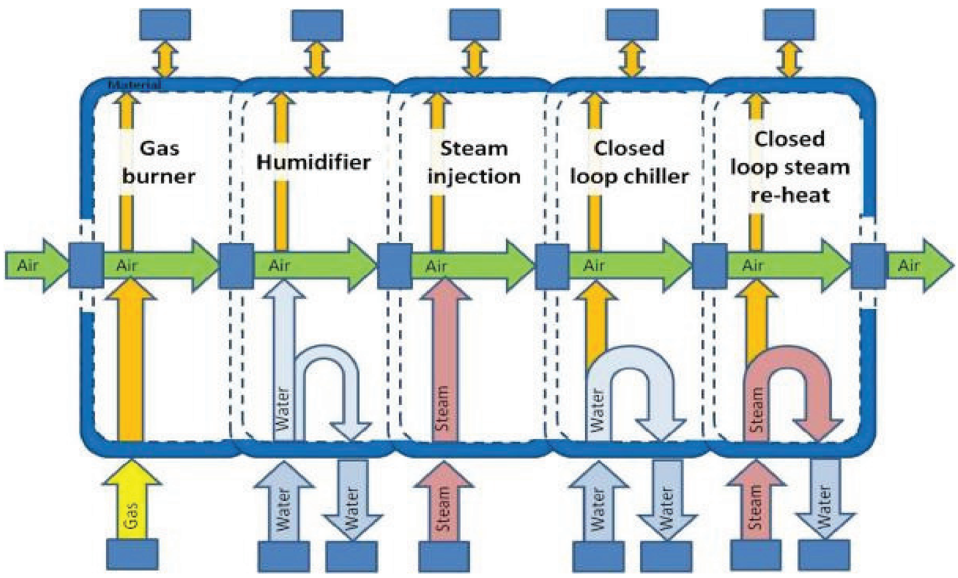

Figure 8 - Graphical representation of a air supply house

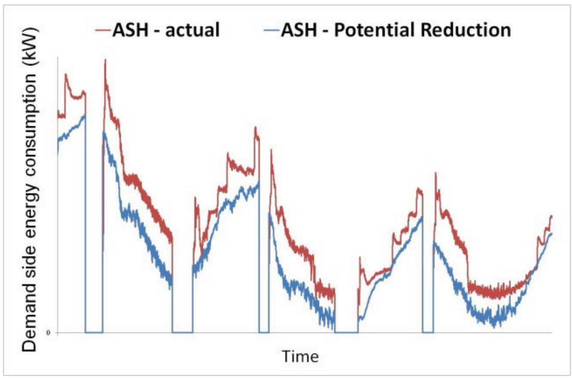

Figure 9 – Reduction tactic

4 CONCLUSION

This paper has described the features of an integrated approach that combines elements of tools for sustainable building design and sustainable manufacturing process design, to achieve an 'Integrated Sustainable Manufacturing' system. Case studies from the industrial partners of the THERM project have been presented to illustrate the development and use of the integrated tool. The methodology and workflow embodied in the tool have been applied to the case studies, identifying significant opportunities for the prevention and reduction of resource waste and the substitution of technology and resource input. The commercial version of the integrated tool is in the late stages of coding, but when it is released and as it is developed, it will provide the ability to model complex networks of existing production systems for whole factories. Through modelling of whole sites or individual factories, advanced tactics such as reuse may help to identify improvement opportunities that would otherwise be difficult to model. Reuse implies both the ability to reuse process outputs that would otherwise be wasted and the synchronisation of these outputs with demand from other factory processes.

5 FUTURE WORK

The case studies described above are to be implemented and analysed using a beta version of the THERM tool.

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